Pumped Hydro Energy Storage: A Plausible Solution to Renewable Energy Reliability

Carina Grady
5 December 2018

1. Abstract

Implementing renewable solar and wind energy is key to living in a sustainable world, but it is deemed unreliable due to its intermittent nature. Energy storage is one solution to this by operating on storing energy when demand is low, then releasing the energy when demand is high. Pumped hydro energy storage dominates the energy storage market, and for good reason: it has a high power capacity, long lifetime, and fast peak-load ramp time. This paper examines the advantages, disadvantages, costs, environmental impact, and challenges the system faces to determine if it can complement intermittent renewable energy.

2. Introduction

According to the National Academy of Engineering, the greatest engineering achievement of the 20th century is electrification [1]. With electrification, humanity was able to achieve incredible technological advancements: the automobile, computer, aircraft, and more. However, as time went on, it became clear that pollution was a dire consequence for energy, and with pollution comes climate change. To slow down climate change, the shift to renewable energy is becoming more and more pressing. From 2017 to 2035, the EIA predicts that renewable energy will double its growth rate in the US [2]. Although renewable energy uses natural resources, there is still one significant drawback that sets the power supply apart from fossil fuel power plants: the energy source is intermittent.

The power grid is built for a continuous, steady supply of electricity that closely matches the demand, and this can be controlled with conventional power plants. Renewable energy, on the other hand, cannot be controlled; wind can be unpredictable, and the sun only shines for half of the day. Without changing the operation of the power grid, renewable energy can be quite unreliable. One solution that solves the intermittency of renewable power is an energy storage system (ESS). Pairing renewable energy with an ESS is a relatively new idea, and so current research is being conducted to determine the most effective solution [3]. However, 94% of global ESS utilizes the oldest yet most effective system available: pumped hydro energy storage (PHES) [3, 4]. This essay explores the technology, costs, advantages, disadvantages, environmental impact, and barriers of PHES utilization to determine whether PHES is a viable solution to reliably store excess renewable energy.

3. System Description

As previously stated, 94% of all ESS consists of PHES, which can be visualized in Figure 1 below. It is the oldest form of storage that is able to store hundreds of megawatts of electricity in the form of potential energy, and perhaps it is the simple physics behind the technology that makes it so appealing.

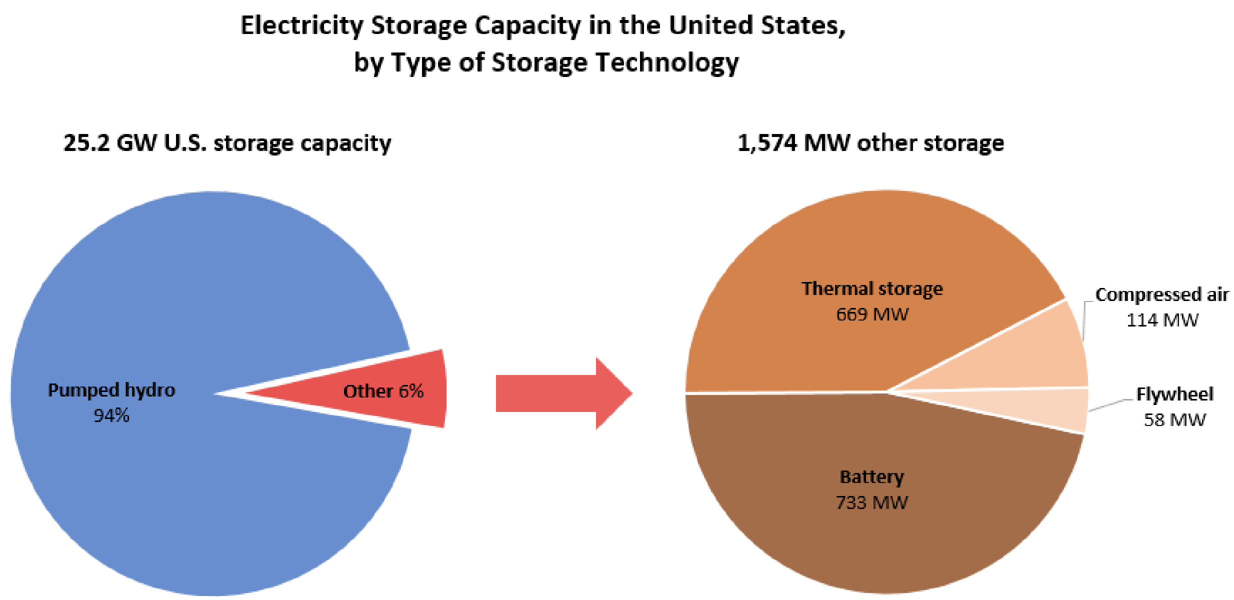

Figure 1: PHES consists of 94% of all USA ESS in 2018 [4]

PHES adopts gravitational potential energy to drive the turbines that spins the generator to produce electricity. To accomplish this, two reservoirs of water are required: an upper basin and a lower basin, separated by a significant vertical distance or pressure head. There are two types of PHES facilities: pure (closed-loop) and pump-back (open-loop). A pump-back PHES facility includes rivers or other natural streams of flowing water, and the one-way direction water flows through a turbine from an upper to lower reservoir, similar to a conventional hydroelectric power plant [5]. For this paper, only pure PHES is considered. A visual of this setup is shown below in Figure 2.

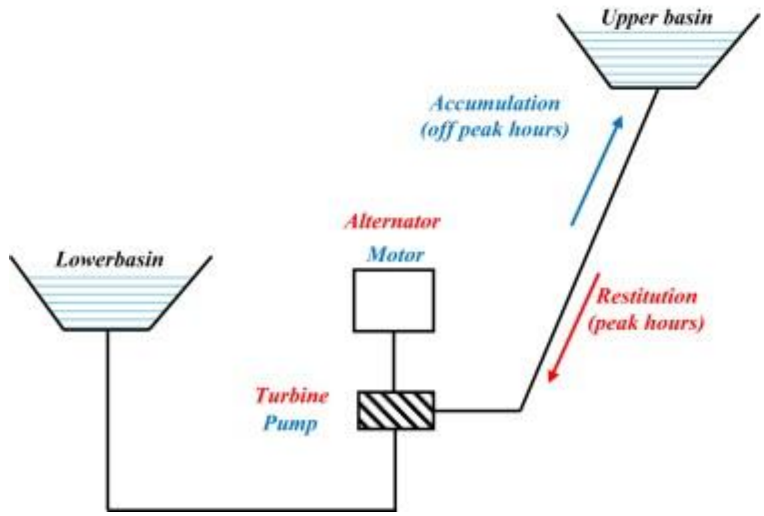

Figure 2: Visual representation of how PHES works [6]

For pure PHES, a pump, turbine, and generator sits between the two reservoirs. When the demand for electricity is low, the water from the lower basin is pumped to the upper basin. When the demand for electricity is high, the water from the upper basin is allowed to flow back down to pass through the turbine that spins the generator to produce electricity [3, 5, 6].

As previously stated, PHES utilizes gravitational potential energy of the freefalling stream of water from the higher to lower basis to spin the turbines. The power output equation is similarly reflected in the formula of a pump that is shown in Equation 1, while the equation of stored energy capacity is shown in Equation 2 [7]. Reference Appendix A for the nomenclature of the equation.

$$P[W] = \rho g Q \Delta h \, \eta \qquad \text{(Equation 1)}$$

$$E[J] = \rho g V \Delta h \, \eta \qquad \text{(Equation 2)}$$

The specific weight (ρg) is relatively constant for each PHES facility, and efficiency is given to be approximately 70 to 85%. Therefore, the volumetric flow rate and height difference are the changing variables that determines the power output, while for energy, the volume and height difference are the changing variables. To maximize power or energy, both of these variables must be as high as possible. This means that a significant volume of water is needed, as well as a mountainous area that leads to a substantial height change.

To demonstrate how these two variables change the energy capacity output, two PHES facilities—Helms and Ludington—are considered with their respective volume of water and reservoir height difference, shown below in Equations 3 and 4. The Helms height is given to be 1744 ft (532 m) with a volumetric flow rate of 9000 ft^3/s (255 m^3/s) [8]. The Ludington height is given to be 320 ft (98 m) with a volumetric flow rate of 66,000 ft^3/s (1886 m^3/s) [9]. Helms has a larger elevation but smaller flow rate, and Ludington has a larger flow rate but smaller elevation. The combined product of the two variables results in a larger power output, as seen in Equation 4 for Ludington. Note that the equations below utilizes approximate numbers to demonstrate how flow rate and elevation changes power; the calculated power does not reflect the actual rated power of the PHES facility.

Helms: $P = (1000\frac{kg}{m^3})(9.81\frac{m}{s^2})(255\ \frac{m^3}{s})(532\ m)(0.80)(10^{-6})$= 1065 MW (Equation 3)

Ludington: $P = (1000\frac{kg}{m^3})(9.81\frac{m}{s^2})(1886\ \frac{m^3}{s})(98\ m)(0.80)(10^{-6})$= 1451 MW (Equation 4)

It is important to note that PHES is *not* a power generation plant; instead, PHES stores excess energy from the grid when demand is low, then places the energy back into the grid when the demand is high. The energy that is required to pump the water from the lower reservoir to the upper reservoir is more than the energy collected by the generator when the water flows from the upper reservoir to the lower reservoir. This is due to various losses such as friction and evaporation, hence why the efficiency is in the range of 70 to 80% [10]. Because of this, it is not cost-effective for the PHES facility to be in operation when demand is neither high or low. With this in mind, PHES can be classified as a peaking rather than base load plant since its operations is dependent on demand.

4. Cost Comparison

Since PHES is not a base load plant that is operating at all times, the levelized cost of electricity (LCOE) is expected to be higher than normal. As a general rule, the more a power generation facility is utilized, the lower the LCOE. Because PHES has a higher capital cost, this especially holds true; the facility is only worth being built if it will be utilized daily.

Helms and Ludington are two PHES facilities that are studied in Table XX-XX to observe the correlation between costs and utilization rate. Both of these closed-system facilities are located in the US and were constructed in the 1980s, and they vary in capacity and in costs, as seen in Table XX below [11]. Note that the power capacity data was taken from the original specification sheets from 1970-1980s, and may not correctly be reflected in today's time. For both facilities, the minimum attractiveness rate of return is assumed to be 7% with a lifetime of 50 years.

Table 1: Comparison of Helms and Ludington PHES at 2018 dollars [11]

PHES Facility	Capacity (MW)	Total Capital Cost (Millions, 1980 Dollars)	Capital Cost in 2018 Dollars (Millions)	$/kW$_{installed}$ in 2018 Dollars
Helms	1050	$600	$1,841	$3,254
Ludington	2076	$322	$988	$549

To observe the differences between a low and high utilization rate, two different cases are calculated at 1095 hours/year and 50 hours/year. Table XX demonstrates the first case at which the PHES facility is utilized at a rate of 1095 hours per year, or 3 hours per day, as shown below. Water costs as well as operation and maintenance (O&M) costs have been omitted for the simplicity of the study.

Table 2: LCOE comparison of Helms and Ludington PHES with utilization of 1095 hr/yr

PHES Facility	Annualized Costs ($Billions/yr)	Energy Consumed (GWh/yr)	LCOE ($/kWh)
Helms	$25.407	1149.75	$22.10
Ludington	$13.635	2273.22	$6.00

Again, because PHES is a peaking plant, the LCOE is expected to be much higher than a typical base load plant. To determine the relative difference of the LCOE, a second case is studied with a utilization rate of 50 hours per year, or 8.2 minutes per day, as seen in Table XX below.

Table 3: LCOE comparison of Helms and Ludington PHES with utilization of 50 hr/yr

PHES Facility	Annualized Costs ($Billions/yr)	Energy Consumed (GWh/yr)	LCOE ($/kWh)
Helms	$25.407	52.5	$483.95
Ludington	$13.635	103.8	$131.36

With these two tables, it can be seen that the utilization rate highly influences the LCOE. The first case of 1095 hr/yr is approximately 22X the utilizate rate of 50 hrs/yr, and it is both 22X cheaper for Helms and Ludington to utilize the bigger rate than the smaller one. Although Helms has approximately half of Ludington’s capacity, the capital costs were half as expensive, which leads to higher LCOE rates than Ludington. In summary, in order to drive down the cost per kWh delivered, is vital to maximize the utilization of PHES.

5. Advantages and Disadvantages

See Table XX below for a complete comparison on efficiency, capacity, energy density, run time, response time, lifetime, and capital costs for PHES, underground compressed air energy storage (CAES), and lithium-ion (Li-Ion) battery systems.

Table 4: Comparing specification of PHES with other ESS [12]

Facility	Efficiency (%)	Capacity (MW)	Energy Density (Wh/kg)	Response Time	Lifetime (Years)	Capital ($/kWh)
PHES	70 - 85	1000 - 5000	0.5 - 1.5	Fast (min)	40 - 60	100
Underground CAES	70 - 89	5 - 400	30 - 60	Fast (min)	20 - 40	50
Li-Ion Battery	85 - 90	0 - 50	800 - 10,000	Fast (ms)	5 - 15	2500

PHES has a deeply limited energy density in comparison to CAES and Li-Ion by a few orders of magnitude, which is another reason why PHES requires maximizing its height difference between the reservoirs and exiting volumetric flow rate to maximize the power produced [12]. However, this means that significant bodies of water is needed at a substantial height difference, which typically occurs at mountainous terrain. Unfortunately, such terrain is limited in scope, and is further discussed in Section 7.

The capital cost of PHES wildly varies between each land site. In Table XX, the capital cost of PHES is more than CAES, but less than Li-Ion. As seen in Table XX in Section 4, the capital cost for Helms was three times of Ludington's, despite Ludington having twice the capacity of Helms. Additionally, PHES has a long lead time of about 10 years, which may also affect its capital cost [10].

Despite the drawback on land and costs, it is still no coincidence the PHES is the most popular choice for ESS. Not only is PHES the most developed and long-lived ESS available, but the ramp time is measured in mere minutes, which is ideal for a peaking plant when there is a sudden increase in demand [12]. Most importantly, however, PHES is able to store a large amount of energy. In Table XX, PHES has an order of magnitude or more of power capacity in comparison to CAES and Li-Ion. In a grid built to support large capacity power plants, having a large capacity ESS is desired to support a large plant. Because of this, PHES has historically been paired with a base load power source, such as nuclear power [5, 13]. Nuclear power plants could produce gigawatts of power into the grid, but because the plant cannot be ramped down in a small time frame, surplus energy goes to waste if the demand is low. PHES would ensure that the surplus energy does not go to waste, and thus minimizes the costs associated overgeneration.

6. Environmental Impact

Like conventional hydroelectric power, PHES is considered a renewable energy as water is abundantly found on Earth and not necessarily finite like fossil fuels. However, just like how wind turbines and solar panels have associated greenhouse gas (GHG) emissions from the manufacturing and transportation of materials, PHES also has associated GHG emissions from its construction. To determine the magnitude of these emissions during construction, the following energy-intense activities were assumed to be conducted during construction [14]:

- **Site preparation and reservoir development emissions**: “earth moving, rock quarrying, drilling and blasting, concrete manufacturing and transport and installation of rock fill, earth and concrete dams”

- **Capital equipment emissions**: pumps, generators, transformers, switchgear, transmission systems, and other electrical systems
- **Reservoir emissions**: clearing biomass/trees from land to dig reservoirs and aerobic decay from flooded biomass
- **Decommissioning**: assume that the facility will only be partly decommissioned due to its minimized impact on environment and acceptance in local ecology

For the simplicity of this observation, it is assumed that the variable O&M costs are neglected, and total emissions are considered as CO_2-equivalent. Using a process chain analysis and economic input/output as life cycle assessment tools, the following table can be produced to estimate the total emission rate, in tonnes-CO_2 per MWh:

Table 5: Listing GHG emissions per energy-consuming component during construction [14]

Component	**Life Cycle Energy ($GJ_t/MWh_{capacity}$)**	**GHG Emission Rate (tonnes-CO_{2e}/MWh)**
Dam construction	37.0	3.35
Tunneling/powerhouse construction	38.1	4.52
Electrical equipment	56.5	4.31
Reservoir creation	0.1	2.2
Decommissioning	17.9	1.3
Total	149.6	15.7

To put the 15.7 tonne-CO_2/MWh total emission rate in perspective, eight PHES facilities are studied to implement this number, as listed in Table XX below.

Table 6: List of PHES facilities with its respective rated power and storage capacity [14]

PHES Facility	**Location**	**Completion Date**	**Rated Power (MW)**	**Storage Capacity (MWh)**
Bad Creek	Salem, SC	1991	1000	24,000
Balsam Meadow	Shaver Lake, CA	1987	200	1,600

Bath County	Warm Springs, VA	1985	2100	23,100
Clarence Cannon	Center, MO	1984	31	279
Fairfield	Jenkinsville, SC	1978	512	4,096
Helms	Shaver Lake, CA	1984	1206	184,000
Mt. Elbert	Leadville, CO	1981	200	2,400
Raccoon Mtn.	Chattanooga, TN	1978	1530	32,130
Rocky Mtn.	Armuchee, GA	1995	760	6,080

Table XX below determines the estimated GHG emission per PHES facility by multiplying the total GHG emission rate by different PHES storage capacities to obtain the tonnes-CO2 emitted. To compare these numbers, a ratio was divided among all the numbers by the smallest value, Clarence Cannon. For example, Mt. Elbert's ratio is nine, which means that one Mt. Elbert facility is the equivalent GHG of nine Clarence Cannon facilities.

Table 7: Estimated GHG emitted per PHES facility and its relative ratio emitted

PHES Facility	GHG Emitted (tonnes-$CO2_e$)	Ratio of GHG Emitted Compared to Smallest Value
Bad Creek	376,320	86
Balsam Meadow	25,088	6
Bath County	362,208	83
Clarence Cannon	4,375	1
Fairfield	64,225	15
Helms	2,885,120	659
Mt. Elbert	37,632	9
Raccoon Mtn.	503,798	115
Rocky Mtn.	95,334	22

Upon seeing the results of Table XX, it is clear that GHG emitted is directly proportional to the storage capacity of the PHES facility. Intuitively, this makes sense; as storage capacity increases, the required reservoir volume increases, which results in longer construction time and thus increasing GHG emissions. This can be seen by comparing Helms (the largest GHG emitter) and Clarence Cannon (the smallest GHG emitter). Helms has approximately 659X the storage capacity of Clarence Cannon, and thus 659X the GHG emitted.

However, this number is merely an estimate and assumed a constant emission rate. Each land has its own different terrain, which directly affects the emission rate. For example, perhaps there were many more trees that had to be removed at Clarence Cannon than Mt. Elbert, which greatly would greatly increase GHG emissions. Or perhaps some facilities utilized natural reservoirs, which would greatly decrease construction time and thus GHG emissions.

Comparing the life cycle assessment of emissions for a natural gas combined-cycle (NGCC) peak-load plant and a PHES facility would be interesting, and studies suggests that the life cycle assessment of emissions for a NGCC system is around 499.1 g-CO_{2e}/kWh, or 0.4991 tonne-CO_{2e}/MWh [15, 16]. This number is much higher than the 15.7 tonne-CO_{2e}/MWh rate for evaluated for PHES, which begs the following questions: is NGCC truly more environmentally friendly over its entire plant life, or is further research needed to evaluate the life cycle emission assessment of PHES? Unfortunately, the answer to this question is outside the scope of this paper, and requires further analysis.

7. Barriers and Challenges

Although PHES is a widely accepted form of ESS, challenges and barriers prevent it from typically complementing base load plants. Costs and potential environmental impacts may be the driving factor of constructing new PHES facilities, but it may also be the cost and scarcity of available land. As quoted from a journal publication:

> An ideal site for pumped hydro storage should provide large elevation between the reservoirs, high power potential, large energy storage capacity, insignificant adverse environmental impact and proximity to power transmission lines … Unfortunately, such an ideal site never exists. [3]

To demonstrate how much PHES depends on land, Figure XX below displays the map of the US with all of its installed PHES facilities. The majority if PHES facilities are towards the west and east; specifically, the Appalachian Mountains and Sierra Nevada. For reference, the greener parts of the maps represent a large elevation in the land, while the whiter parts of the map represent a level or flat part of the land The Midwest lacks mountainous areas, and thus lack PHES facilities.

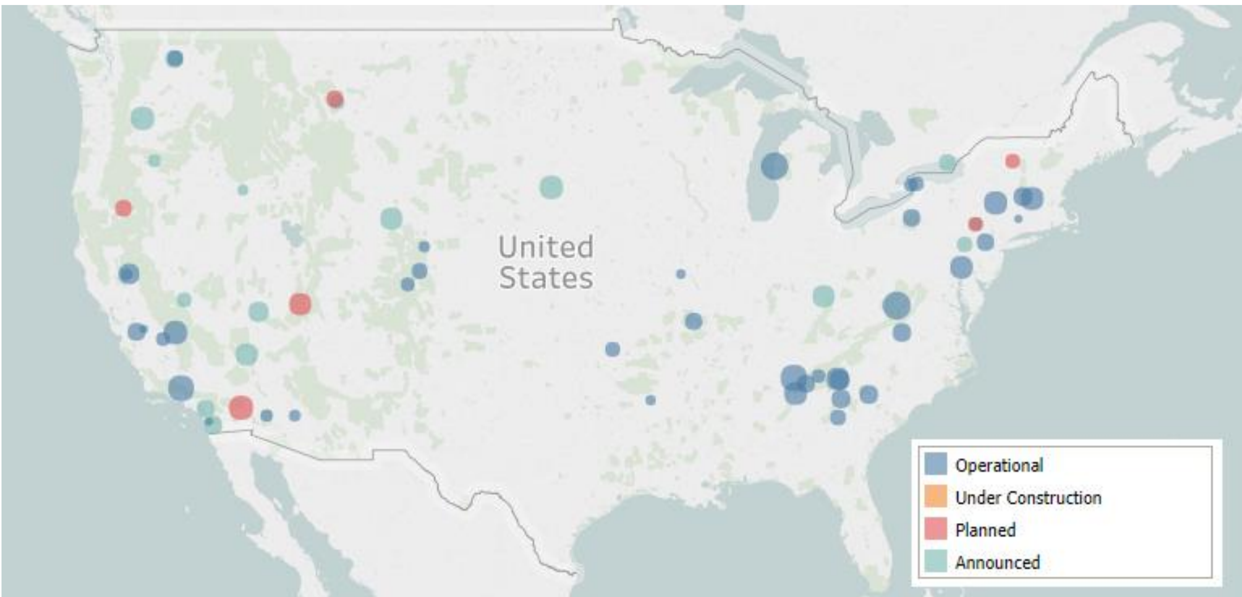

Figure 3: Map of operational, planned, and announced PHES facilities in the US [7]

Fortunately, there is still substantial estimated amount of capacity that has not yet been installed. According to XX, "Pumped hydro capacity was estimated to be between 120 GW and 150 GW with a central estimate of 136 GW," [18] but this number merely estimates the available land that can be converted to PHES facilities. A land may be available, but other considerations must also factor into the decision of constructing a PHES facility. For example, is there significant amount of wildlife in the area that will have to be removed to create reservoirs? And is the land too isolated and thus too far away from an electrical substation?

Perhaps the land is in a national park or forest where wildlife is preserved and requires destruction of habitat to create a PHEs facility, or perhaps the land is too far from an electrical substation that transmission costs would be too high.

In short, the challenges of finding an ideal land location and minimizing its corresponding costs and environmental impact present the larger barriers for growth of PHES, but economically, there is one other barrier that has been undiscussed: the history and low cost of natural gas. As of 2017, 95% of the available ESS comes from PHES, with 43 PHES plants totaling to a capacity of 21.6 GW [19]. This results in the US having the third largest PHES capacity of the world, yet only one PHES facility has been open since 2006. This growth is dismal in comparison to the world; in the same time period, 22 PHES facilities were constructed in East Asia, and 9 were constructed in Europe. The US may be lagging behind for PHES growth, but from 1960s through 1980s, PHES growth was astounding, increasing from nearly 0 MW capacity to 20,000 MW [13]. Also during this time, nuclear power became increasingly popular, and it was thought that PHES was vital to complement the base load nuclear power [13]. Therefore, when the growth of nuclear power halted in the 1980s, so did the growth of PHES. With the rise of hydraulic fracturing in the 1990s, a new type of peak-load plant was introduced: natural gas combined-cycle (NGCC) plants. During the 1980s and 1990s, natural gas prices became relatively low, and technological advancements have made NGCC more inexpensive, faster to construct, and more widely available [20]. Since then, NGCC became a direct peak-load competitor to PHES, and still is today. Instead of asking whether PHES can replace peak-load NGCC, perhaps the better question is to ask at what cost of natural gas is

PHES more favorable? Although this topic is outside the scope of this paper, it is an interesting subject on its own and deserves further analysis.

8. Conclusion

If renewable energy is treated as a base load where it is always operating, then based on its intermittent nature, there will be times when there is too much or too little electricity produced, and so a peaking plant with a fast ramp time is needed to stabilize the grid. One non-fossil fuel solution to this is ESS, or specifically, PHES, which involves two reservoirs of water at different elevations. In essence, PHES is like a mechanical battery conducted by water and gravity, but it is dictated by demand; when demand is low, water is pumped to the higher reservoir, and when the demand is high, water flows down to the lower reservoir and spins a turbine and generator. To maximize the power output, the volumetric flow rate and change in elevation between the two reservoirs are maximized. PHES is the most developed ESS technology and dominates 94% of all installed storage, perhaps because it is the only long-lasting developed technology so far that is able to store thousands of megawatts in a fast ramp time.

However, all energy systems come with disadvantages. Although PHES can be designed to have a large power capacity, this can only be done with large bodies of water at a significant elevation change due to its low energy density. Larger reservoirs mean longer construction time, which could take up to 10 years, and be very expensive. Due to its higher capital cost of construction, the LCOE can be incredibly expensive if the facility is not much utilized. Additionally, the life cycle assessment of PHES finds that GHG emissions are found in the construction of the facility. The majority of the GHG emissions come from the construction of the reservoir and the removal of biomass.

The challenges that prevent PHES from being more widely available come mostly from the land available. Unlike NGCC plants where it can be placed anywhere, a steep elevation change is needed to operate a PHES facility, which already eliminates many naturally-leveled areas such as the Midwest. Other factors also come into consideration for land choice, such as environmental impact, transmission costs, and capital costs. Currently, peak-load NGCC plants are a cost-effective option, and it is a direct competitor to the renewable PHES market. Because PHES was originally built for complementing nuclear power, when the nuclear industry stalled in the 1980s, so did the PHES industry. Thus, when technological advancements in hydraulic fracturing occured and dropped the prices of natural gas, NGCC plants overtook PHES as a popular choice for peak-load, and still is to this day.

With all of this in mind, the question can be answered: is PHES a viable solution to reliably store excess intermittent renewable energy? It is plausible, but it is also unreasonable to think that PHES is the only ESS solution. With the correct policy and commercial incentive to construct more PHES facilities, it may very well be a replacement to peak-load NGCC plants, which already helps stabilize existing renewables. However, unlike NGCC plants where the location can be placed nearly anywhere, PHES facilities are constrained to certain locations and require a thorough cost and environmental life cycle assessment. Perhaps PHES would be a reliable solution to storing wind and solar energy near the Appalachians where reservoirs and elevation changes are more abundant, but the same cannot be said the same in the Midwest where land is more leveled.

It can be noted that the original memo referenced in Appendix B is found to be ambitious; upon closer examination and research, being able to answer whether PHES is "the solution" to renewable energy is much more complicated than anticipated. Too many factors exist to be able to form a concrete answer, and many of those factors are outside the scope of this paper. More research is needed to clarify a clearer solution of the complex problem that is intermittent renewables, such as:

- Renewable and PHES grid stability and how often curtailment occurs.
- Life cycle cost and emission differences between a base load plant with a peak-load NGCC versus PHES at the same power capacity and storage/output.
- Case studies on emissions on a PHES facility with an existing reservoir versus man-made reservoir.
- Other possible reasons on why the US is lagging on PHES, such as policy.
- More in-depth analysis on how natural gas costs affect PHES utilization
- Historic analysis on how natural gas costs affect number of PHES facilities.
- Comparisons of costs and environmental impact of other available ESS, such as CAES.

The last point is important; although PHES may work very well in some areas, it is not a universal solution to energy storage. To truly live in a sustainable world, a variety of ESS must be considered to complement renewable energy, and PHES is just one of the many that are just emerging that can help stabilize intermittent renewable energy.

9. References

1. Wulf, A. Wm. “Great Achievements and Grand Challenges.” *The Bridge*, vol. 30, no. 3 and 4 (2000): pp. 5-10. National Academy of Engineering. Web. 1 December 2018.
2. *Annual Energy Outlook 2018*. Energy Information Administration, 2018. Web. 1 December 2018.
3. Mahlia, T. M. I., et al. “A review of available methods and development on energy storage; technology update.” *Renewable and Sustainable Energy Reviews*, vol. 33 (2014): pp. 532-545. ScienceDirect. Web. 20 November 2018.
4. *Electricity Storage.* United States Environmental Protection Agency, 2018. Web. 23 November 2018. https://www.epa.gov/energy/electricity-storage.
5. Deane, J. P., et al. “Techno-economic review of existing and new pumped hydro energy storage plant.” *Renewable and Sustainable Energy Reviews*, vol. 14 (2010): pp. 1293-1302. ScienceDirect. Web. 20 November 2018.
6. Kousksou, T., et al. “Energy storage: Applications and challenges.” *Solar Energy Materials and Solar Cells*, vol. 120 (2014): pp. 59-80. ScienceDirect. Web. 20 November 2018.
7. *Pump Power Calculator*. Engineering ToolBox, 2003. Web. 1 December 2018. https://www.engineeringtoolbox.com/pumps-power-d_505.html.
8. *By the Numbers: Helms Pumped Storage Facility.* Pacific Gas & Electric, 2011. Web. 1 December 2018. http://www.pgecurrents.com/2011/10/17/by-the-numbers-helms-pumped-storage-facility/
9. *Application for New License for Major Project – Existing Dam Ludington Pumped Storage Hydroelectric Project*. Consumers Energy Company, DTE Electric Company, 2017. Web. 1 December 2018. FERC NO. 2680.
10. Chen, Haisheng, et al. “Progress in electrical energy storage system: A critical review.” *Progress in Natural Science*, vol. 19, no. 3 (2009): pp. 291-312. ScienceDirect. Web. 20 November 2018.
11. *An Assessment of Hydroelectric Pumped Storage*. Dames and Moore, 1981. Web. 1 December 2018.
12. Evans, Annette, et al. “Assessment of utility energy storage options for increased renewable energy penetration.” *Renewable and Sustainable Energy Reviews,* vol. 16, no. 6 (2012): pp. 4141-4147. ScienceDirect. Web. 21 November 2018.
13. Yang, Chi-Jen, Robert. B. Jackson. “Opportunities and barriers to pumped-hydro energy storage in the United States.” *Renewable and Sustainable Energy Reviews,* vol. 15, no. 1 (2011): pp. 839-844. ScienceDirect. Web. 21 November 2018.
14. Denholm, Paul, Gerald Kulcinski. “Net energy balance and greenhouse gas emissions from renewable energy storage systems.” *Energy Center of Wisconsin* (June 2003). Web. 3 December 2018.
15. Spath, Pamela L., Margaret K. Mann. “Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System.” *National Renewable Energy Laboratory* (September 2000). Web. 3 December 2018.

16. Burnham, Andrew, et al. “Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum.” *Environ. Sci. Technol*, vol. 46, no. 2 (2012): pp. 619-627. ACS Publications. Web. 3 December 2018.
17. *Pumped Storage Tracking Tool*. International Hydropower Association, 2017. Web. 2 December 2018. https://www.hydropower.org/hydropower-pumped-storage-tool.
18. International Renewable Energy Agency. “Hydropower.” *Renewable Energy Technologies: Cost Analysis Series*, vol.1, no. 3/5 (June 2012). Web. 25 November 2018.
19. *2017 Hydropower Market Report*. U.S. Department of Energy, 2017. Web. 25 November 2018.
20. Hittinger, Eric, Roger Lueken. “Is inexpensive natural gas hindering the grid energy storage industry?” *Energy Policy*, vol. 87 (2015): pp. 140-152. ScienceDirect. Web. 23 November 2018.

10. Appendix

10.1. Appendix A: Nomenclature

ESS	energy storage system
GHG	greenhouse gas
NGCC	natural gas combined-cycle
PHES	pumped hydro energy storage
ρ	density (kg/m^3)
g	gravitational constant (9.81 m/s^2)
Δh	pressure head; change in height or elevation (m)
Q	volumetric flow rate (m^3/s)
η	efficiency
V	volume (m^3)

10.2. Appendix B: Memo

As the world population continues to grow, so does energy demand. But with recent threats of climate change and poor air quality, the demand for clean energy has boomed. According to the EIA, from 2017 to 2035, the growth of renewable energy in the US is predicted to increase by 50%. A significant growth like this means the US is one step closer to slowing down climate change, but there is one critical drawback: renewable energy isn't as reliable as fossil fuels.

Unlike burning fossil fuels, the sun and wind is not able to be controlled. This introduces serious issues in matching energy demand in the grid, so renewable energy is paired with gas-fired peaker plants to offset the difference. Having to pair fossil fuels with renewable energy defeats the purpose of a "clean" energy intention, but fortunately, there is a solution: energy storage. The purpose of energy storage is to store surplus energy (mostly from renewable sources) when demand is low, then use the energy when the demand is high. There are many types of energy storage sources, such as: lithium-ion batteries, pumped-storage hydropower, compressed air, flywheels, and more. However, pumped storage hydropower is the oldest form of energy storage, and so it is also the most understood.

The world is entering an exciting shift for cleaner energy, so for my energy analysis report, I aim to answer the following question: *Is pumped hydroelectric storage a viable solution to store excess renewable energy power?*

To answer this question, pumped hydroelectric storage must first be understood and completely
analyzed. I have broken down an outline for my report that will answer the following questions:

- **System Description**: What is pumped-storage hydroelectricity? How does this system work to provide electricity? Is the pumped-storage more of a base-load or peaker? How much electricity is needed to pump the water?
- **Land Use**: Where can pumped-stored facilities be built? What is the estimated US capacity (in GW) for pumped-storage systems? How long is the lifecycle of the facility?
- **Costs**: How much are capital/construction costs? What is the cost per kwh? Is this more expensive than gas-fired peaker cost per kwh? If utilized daily, would the system be cost effective? If not utilized daily, would the system be cost-effective?
- **Examples**: What's a real-life example of a successful pumped-storage facility? What's a real-life example of an unsuccessful pumped storage facility?
- **Impact**: How many kilograms of released CO_2 would be saved per year if the US maximized its pumped-storage capacity instead of using gas-fired peaker plants? How many kilowatt-hours is estimated to be 'lost' due to surplus renewable energy, and how much does that compare to the estimated US capacity for pumped-storage?

Answering the questions above, enough research would have been done to determine whether or not pumped hydroelectric storage is a reasonable solution to solve renewable energy's storage problem. This is based on cost, environmental, and land/energy capacity factors.